Remote sensing of hydrological drought based on precipitation and evapotranspiration estimates

Jinyoung Rhee
Climate Change Research Team
Climate Research Department

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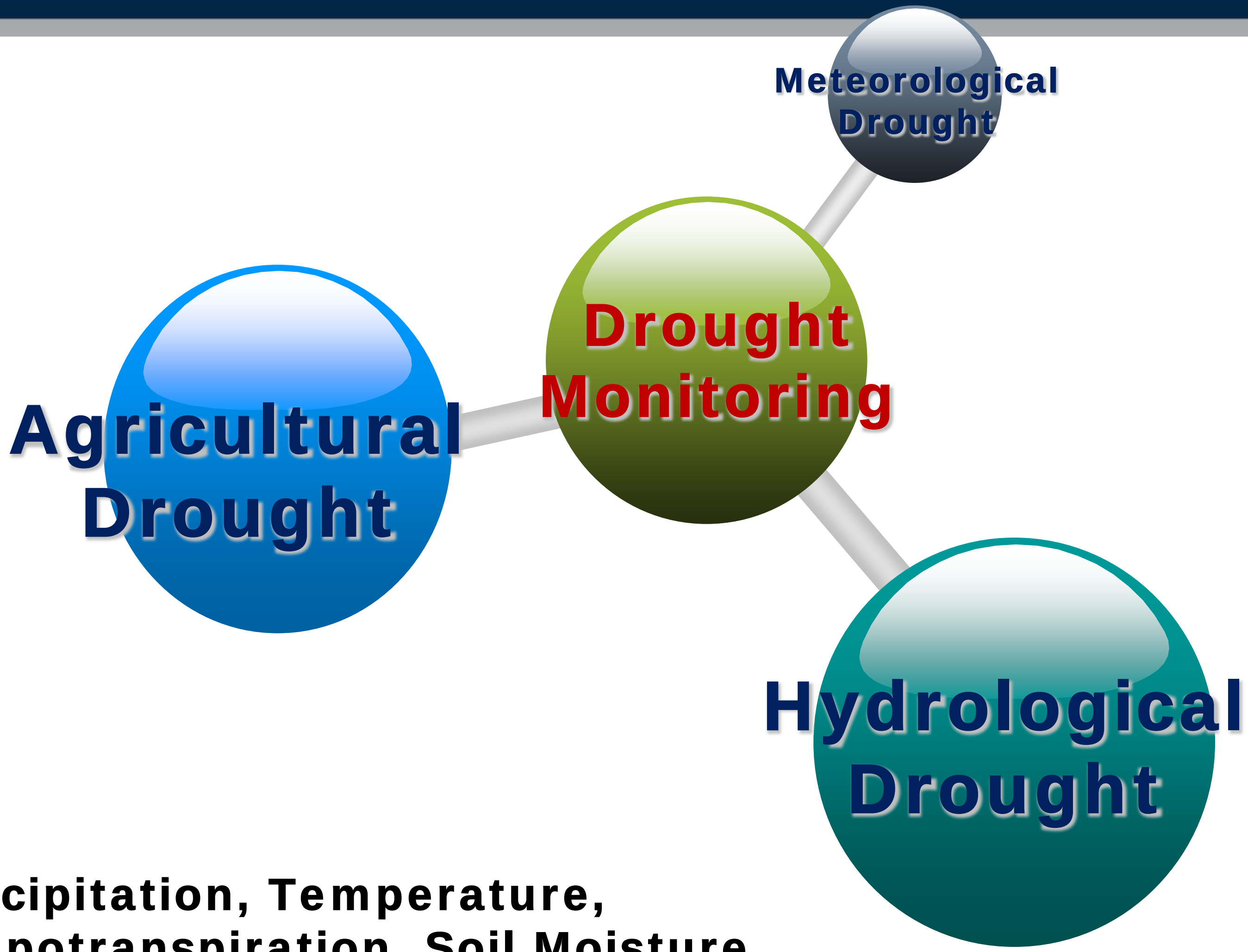
APCC APEC CLIMATE CENTER

Drought Assessment and Monitoring



Precipitation, Temperature, Evapotranspiration, Soil Moisture, Streamflow, Runoff, etc.

Hydrological Drought

- **"Hydrological droughts are concerned with the effects of periods of precipitation shortfall on surface or subsurface water supply" (AMS)**

- **Improved irrigation systems**
  - Dams, reservoirs, etc.

- **Still occurs severe & extreme drought**
  - e.g. 2008~2009, 2012 drought in South Korea

Ungauged Basins

- Limited measurements of meteorological and hydrological variables

- Estimation based on water balance using
  - Statistical methods
  - Hydrological / land surface models
  - Remote sensing

Uncertainty

- **“Whether more reliable estimation … can be obtained from physically-based methods … with uncertain data quality, or more empirical methods … with more reliable input data”** (Kingston et al., 2009)

Research Question

- **Can the…**
  - Remote sensing-based precipitation and evapotranspiration estimates be used for assessing hydrological drought?

- **Purpose of study**
  - To verify the use of remote sensing-based precipitation and evapotranspiration estimates for assessing hydrological drought in regions with limited observation data

Methodology

Estimating air temperature

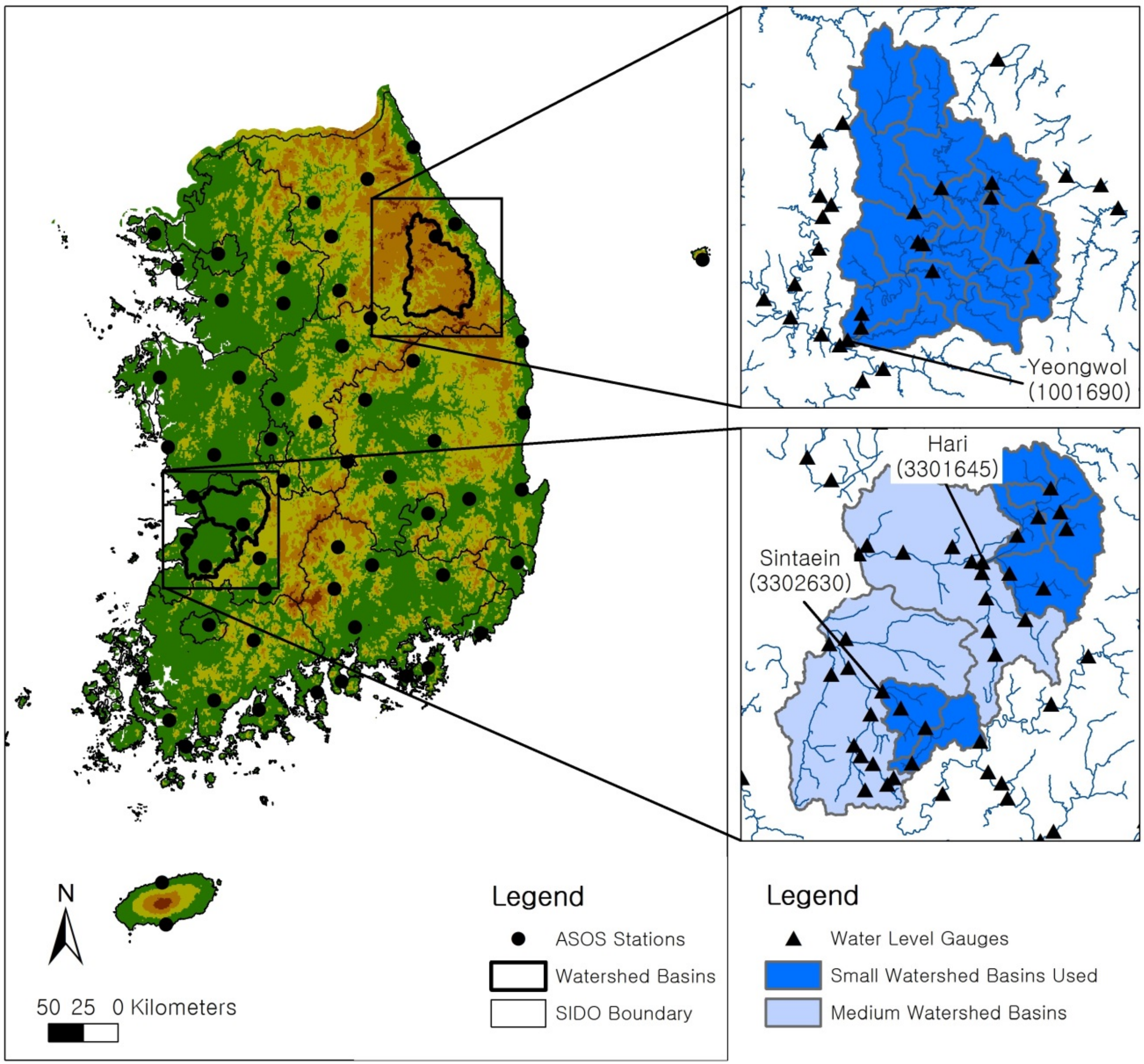
Estimating evapotranspiration

Correlation analysis with streamflow

Hydrological drought assessment

Study Area

60 weather stations



Upper Namhan-gang

Mankyung-gang

Dongjin-gang

5kmx5km grids

Data

- **Remote sensing data**
  - MODIS Land Surface Temperature (MYD11A2)
  - MODIS Atmospheric Profile (MYD07_L2)
  - *TRMM* 3B43 monthly rainfall
  - MODIS Land Cover Type (MCD12Q1)
  - GTOPO30 DEM
- ***In-situ* data**
  - ASOS weather station hourly temperature data
  - Streamflow discharge
  - Calculated PET based on Penman-Monteith

Methodology: Estimating Air Temperature

- **Gridded dataset with maximum and minimum temperature**
  - NCEP/NCAR - 2.5°x2.5° (daily)
  - CRU TS3.20 - 0.5°x0.5° (monthly)
- **Existing studies**
  - NDVI, Elevation, SZA(solar zenith angle), land surface temperature, latitude, longitude, etc.
- **Temperature from LST and AP**
  - LST
  - AP –linear interpolation/extrapolation for 2-m height (620hPa~1000hPa)

Methodology: Estimating Air Temperature

- **Diurnal temperature change model**
- **Correction using CRU TS3.20**

$$T = (T_{\max} - T_{\min})\sin\left(\frac{\pi}{2}\frac{(t - t_{Tmin})}{(t_{Tmax} - t_{Tmin})}\right) + T_{\min} \qquad t_{Tmin} \le t < t_{Tmax}$$

$$T = -\left(\frac{T_{\max} - T_{\min}}{2}\right)\sin\left(\frac{\pi\left(t - \frac{t_{Tmax} + t_{Tmin} - 24}{2}\right)}{t_{Tmin} - t_{Tmax} + 24}\right) + \left(\frac{T_{\max} + T_{\min}}{2}\right)$$

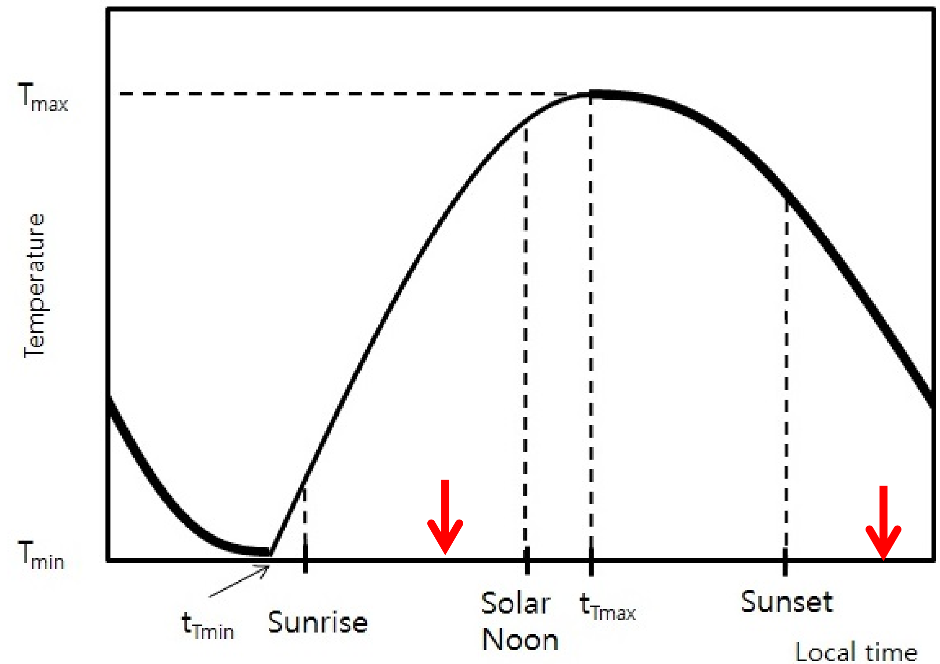
$$0 < t \le t_{Tmin}$$

$$T = -\left(\frac{T_{\max} - T_{\min}}{2}\right)\sin\left(\frac{\pi\left(t - \frac{t_{Tmax} + t_{Tmin} + 24}{2}\right)}{t_{Tmin} - t_{Tmax} + 24}\right) + \left(\frac{T_{\max} + T_{\min}}{2}\right)$$

$$t \ge t_{Tmax}$$

$$t_{Tmin} = t_{Trise} - 1$$

$$t_{Tmax} = t_{Tnoon} + 2$$



The proposed diurnal temperature change model using two sinusoidal functions for ascending (thin-line) and descending (thick-line) air temperature.

Methodology: Estimating Evapotranspiration

- **Assumptions**
  - Soil moisture stress
  - Land cover and vegetation phenology

- **Methods**
  - Penman-Monteith
  - Hargreaves

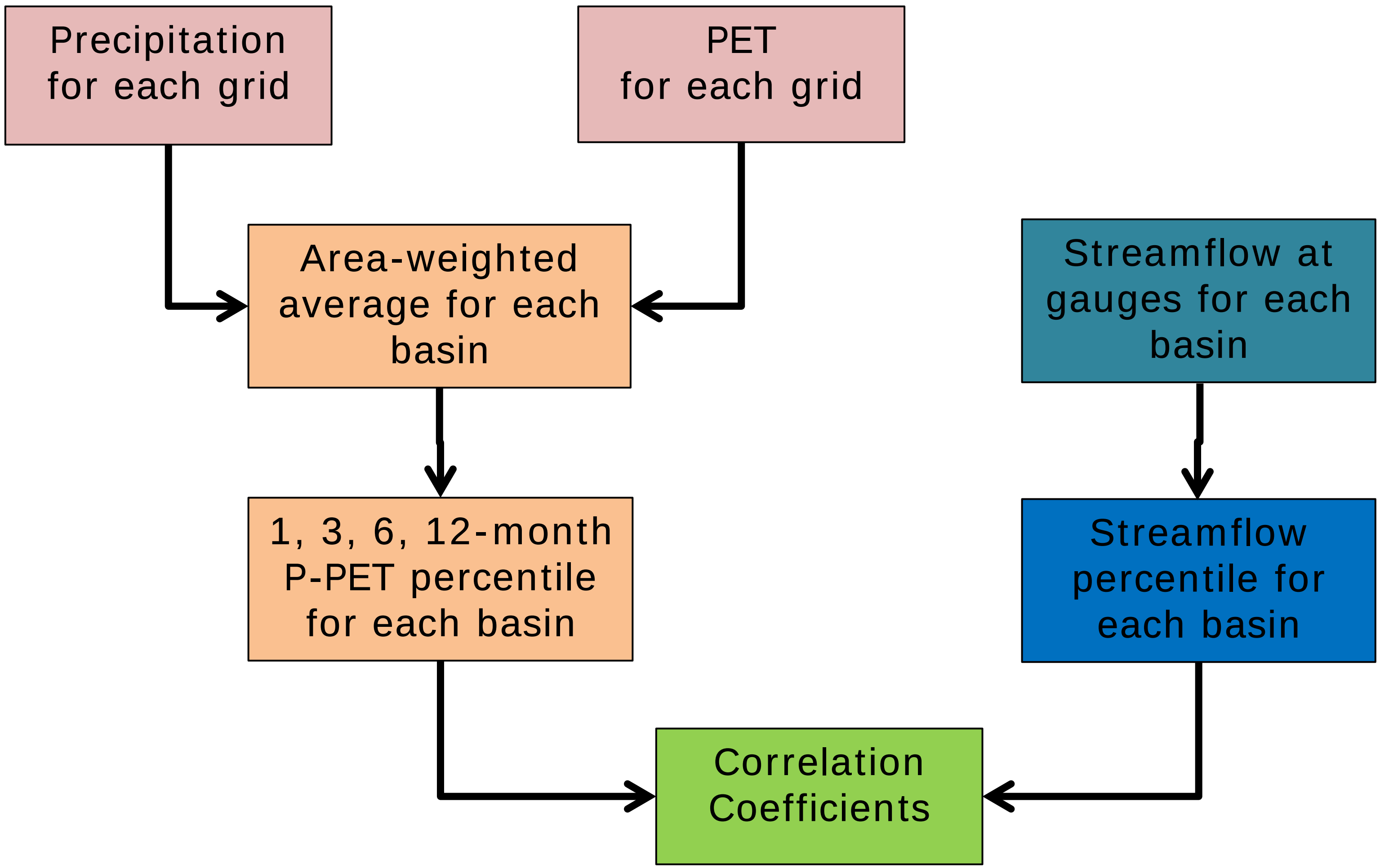
$$ET_o = 0.0023\,(T_{mean} + 17.8)\,(T_{max} - T_{min})^{0.5}\,R_a$$

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34\,u_2)}$$

ET_o	reference evapotranspiration [mm day^{-1}],
R_n	net radiation at the crop surface [MJ m^{-2} day^{-1}],
G	soil heat flux density [MJ m^{-2} day^{-1}],
T	air temperature at 2 m height [°C],
u_2	wind speed at 2 m height [m s^{-1}],
e_s	saturation vapour pressure [kPa],
e_a	actual vapour pressure [kPa],
e_s-e_a	saturation vapour pressure deficit [kPa],
Δ	slope vapour pressure curve [kPa °C^{-1}],
γ	psychrometric constant [kPa °C^{-1}].

(Allen et al. 1998)

Methodology: Correlation Analysis with Streamflow



Results: Estimating Air Temperature

- **Coefficient of determination (R^2)**

Station-averaged coefficient of determination (R^2) values (unitless).

Variable	Season	Corrected			Uncorrected		
		AP	AP_shift	LST	AP	AP_shift	LST
Maximum Temperature	ALL	0.95	0.95	0.94	0.95	0.95	0.94
	MAM	0.89	0.88	0.94	0.89	0.88	0.94
	JJA	0.42	0.44	0.13	0.42	0.44	0.13
	SON	0.92	0.92	0.96	0.92	0.92	0.96
	DJF	0.62	0.58	0.71	0.62	0.58	0.71
Minimum Temperature	ALL	0.94	0.94	0.97	0.94	0.94	0.97
	MAM	0.88	0.88	0.96	0.88	0.88	0.96
	JJA	0.77	0.76	0.75	0.77	0.76	0.75
	SON	0.92	0.91	0.95	0.92	0.91	0.95
	DJF	0.34	0.29	0.48	0.34	0.29	0.48

Results: Estimating Air Temperature

- **MAE (Mean Absolute Error)**

Station-averaged MAE values (unit: °C/month).

Variable	Season	Corrected			Uncorrected		
		AP	AP_shift	LST	AP	AP_shift	LST
Maximum Temperature	ALL	2.14	2.13	2.25	3.61	3.63	2.92
	MAM	2.04	2.05	1.85	4.72	4.64	4.58
	JJA	1.81	1.80	1.94	3.14	3.15	3.38
	SON	1.92	1.92	1.73	3.85	3.82	1.94
	DJF	1.92	1.90	1.86	2.76	2.74	1.88
Minimum Temperature	ALL	2.33	2.38	1.95	2.34	2.17	1.44
	MAM	1.91	1.92	1.64	1.44	1.47	1.18
	JJA	1.46	1.47	1.47	2.10	2.03	1.48
	SON	2.10	2.15	1.89	2.26	1.98	1.27
	DJF	2.19	2.22	2.17	3.94	3.55	1.89

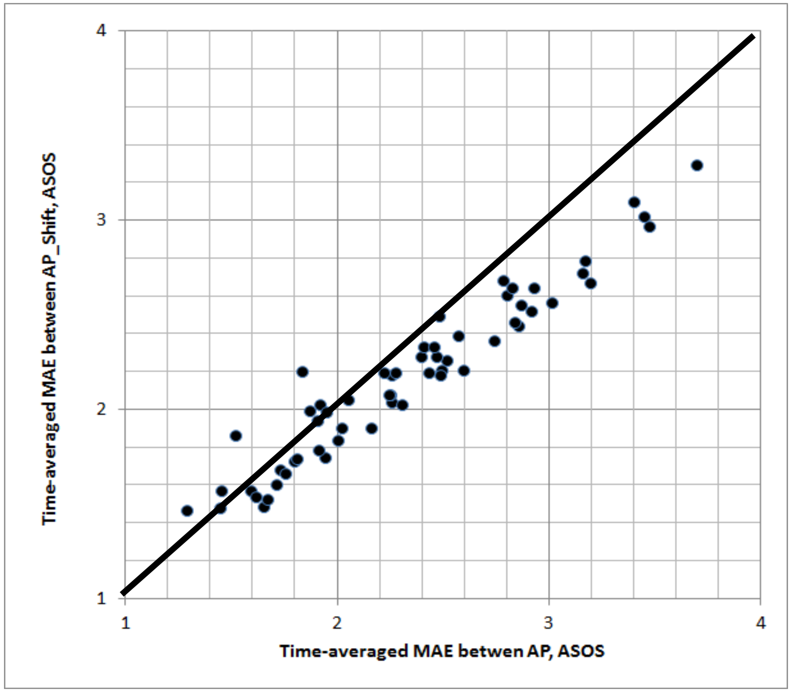
Results: Estimating Air Temperature

- **RMSE (Root Mean Squared Error)**

Station-averaged RMSE values (unit: °C/month).

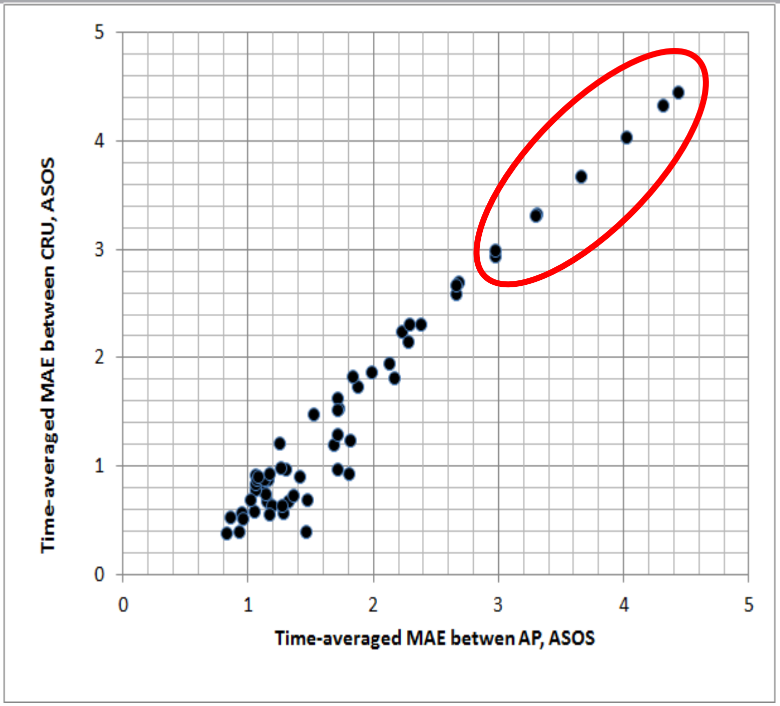
Variable	Season	Corrected			Uncorrected		
		AP	AP_shift	LST	AP	AP_shift	LST
Maximum Temperature	ALL	2.59	2.58	2.72	4.05	4.06	3.51
	MAM	2.38	2.40	2.13	5.02	4.95	4.79
	JJA	2.07	2.06	2.28	3.61	3.62	3.90
	SON	2.24	2.25	1.98	4.16	4.13	2.24
	DJF	2.22	2.19	2.11	3.08	3.07	2.22
Minimum Temperature	ALL	2.81	2.89	2.36	2.91	2.75	1.87
	MAM	2.25	2.26	1.87	1.82	1.83	1.42
	JJA	1.71	1.72	1.72	2.51	2.44	1.81
	SON	2.49	2.56	2.22	2.63	2.40	1.58
	DJF	2.51	2.55	2.47	4.35	4.03	2.36

Results: Effect of Shift, Correction Using CRU



Scatter-plot comparing time-averaged MAE values for minimum air temperature during all season (unit: °C/month): each point represent ASOS weather station.

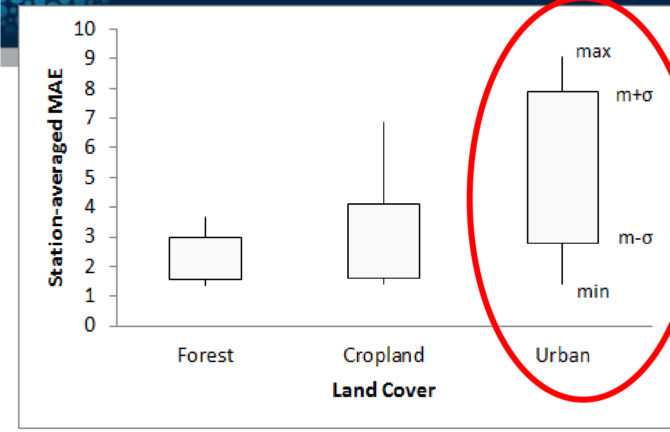
→ Uncorrected, minimum temperature, JJA, SON, DJF



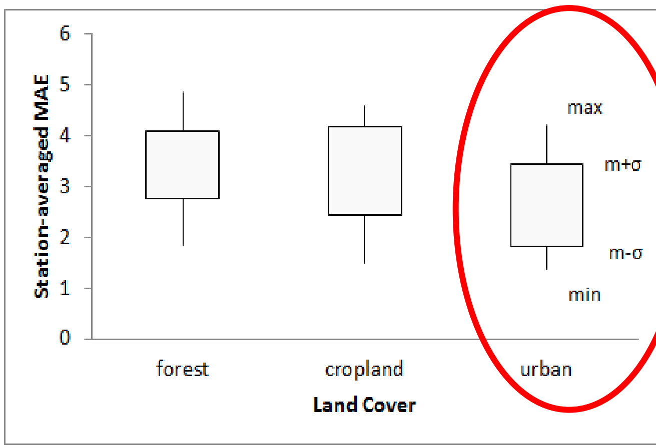
Scatter-plot comparing time-averaged MAE values for maximum air temperature during JJA: each point represent ASOS weather station.

→ New source of error

Results: Effect of Land Cover

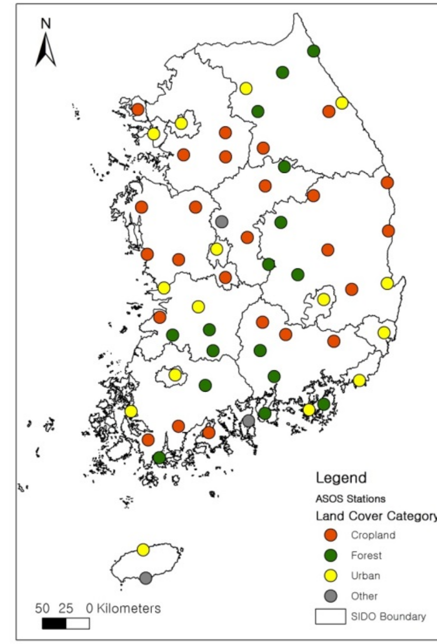


Uncorrected daytime LST vs. ASOS maximum air temperature during JJA



Uncorrected daytime AP vs. ASOS maximum air temperature during JJA

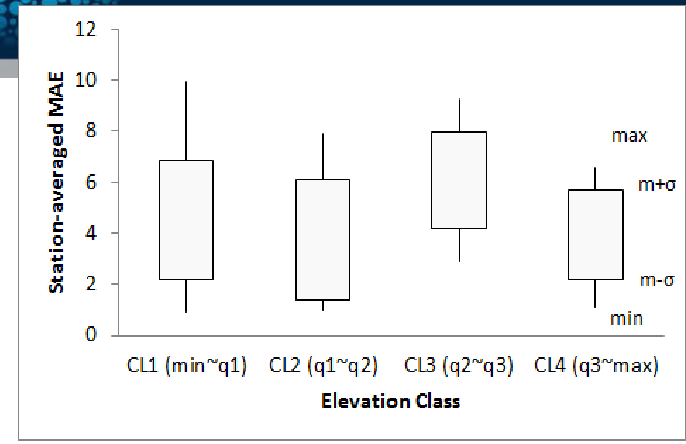
Impervious surface
Heat island effect



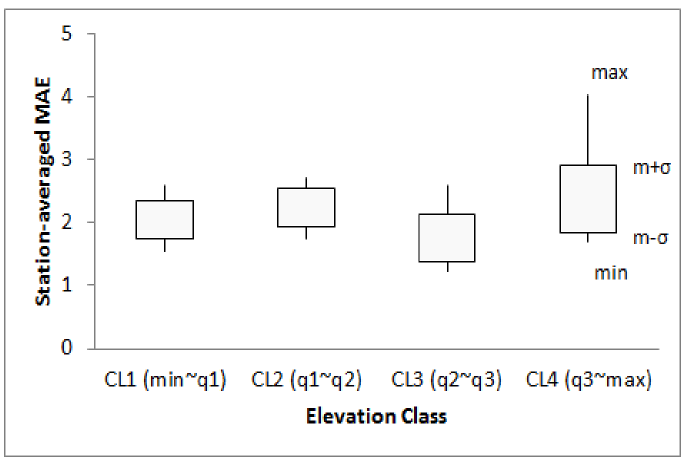
Test statistics for one-way ANOVA testing differences between land cover types.

Variable	Season	Corrected		Uncorrected	
		AP	LST	AP	LST
Maximum Temperature	ALL	0.14	0.16	0.03	<.0001
	MAM	0.06	0.14	0.06	0.0001
	JJA	0.16	0.34	**0.003**	**<.0001**
	SON	0.10	0.12	0.02	<.0001
	DJF	0.50	0.39	0.13	0.06
Minimum Temperature	ALL	0.34	0.16	<.0001	0.68
	MAM	0.05	0.04	0.09	0.37
	JJA	0.09	0.23	0.0005	0.62
	SON	0.43	0.19	0.001	0.91
	DJF	0.21	0.36	<.0001	0.12

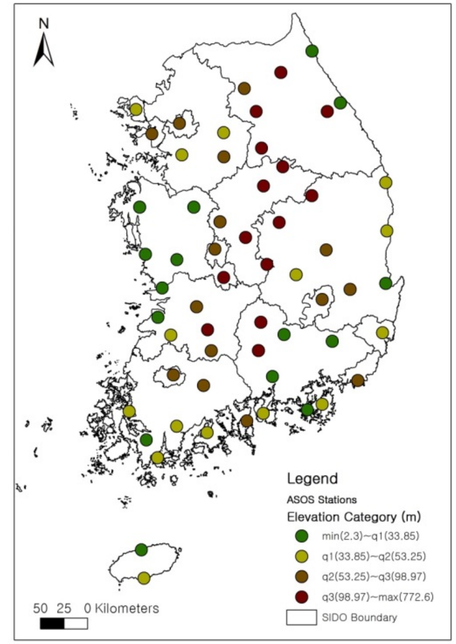
Results: Effect of Elevation



Uncorrected daytime LST vs. ASOS maximum air temperature during MAM



Uncorrected nighttime AP vs. ASOS minimum air temperature during JJA



Test statistics for one-way ANOVA testing differences between elevation classes.

Variable	Season	Corrected		Uncorrected	
		AP	LST	AP	LST
Maximum Temperature	ALL	0.34	0.34	0.06	0.03
	MAM	0.12	0.15	0.06	**0.03**
	JJA	0.44	0.71	0.13	0.04
	SON	0.32	0.42	0.07	0.10
	DJF	0.84	0.81	0.12	0.36
Minimum Temperature	ALL	0.91	0.83	0.03	0.26
	MAM	0.85	0.75	0.42	0.35
	JJA	0.74	0.67	**0.0006**	0.10
	SON	0.53	0.45	0.05	0.47
	DJF	0.83	0.74	0.04	0.28

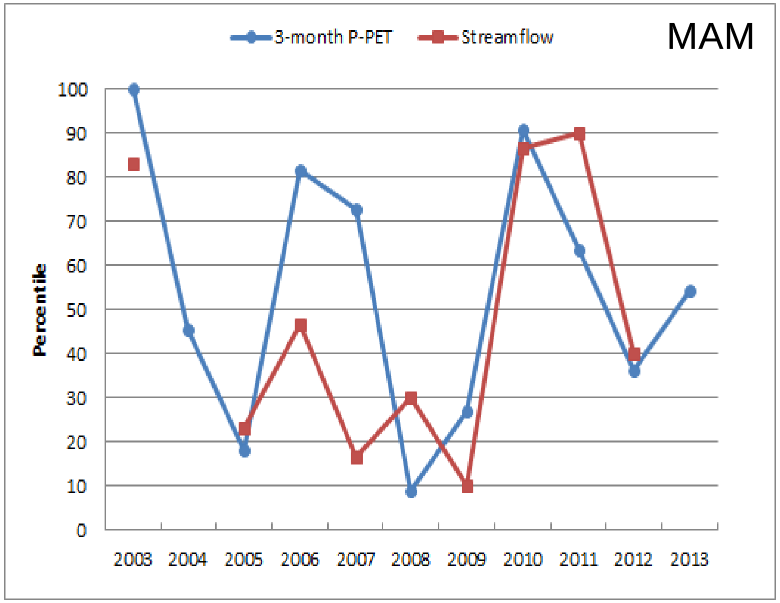
Results: Estimating Evapotranspiration

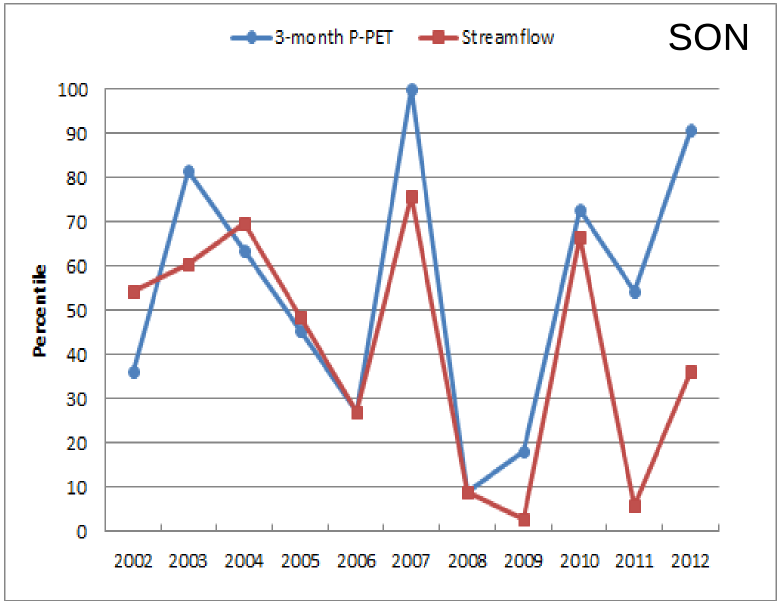
- **Coefficient of determination (R^2), MAE, RMSE**

Season	R^2 (unitless)	MAE (mm/month)	RMSE (mm/month)
ALL	0.90	16.81	21.93
MAM	0.89 (r = 0.94)	25.66	28.20
JJA	0.06 (r = 0.24)	24.76	29.10
SON	0.83 (r = 0.91)	11.12	13.58
DJF	0.57 (r = 0.75)	6.44	7.54

Results: Correlation with Streamflow in Mankyung-gang Watershed Basin

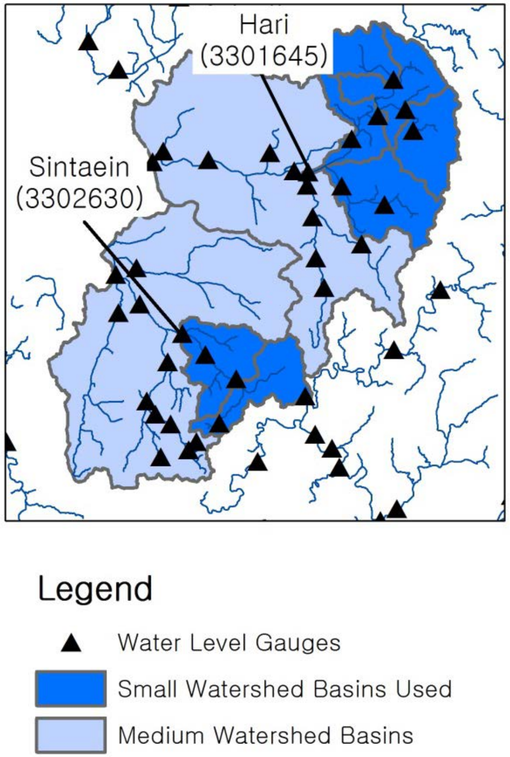
Variable	Time Scale (months)	Season	Sample Size	Pearson' r (p-value)	Kendall's tau (p-value)
P-PET	1	JJA	32	0.88 (<.0001)	0.69 (<.0001)
P-PET	3	MAM	9	0.67 (0.05)	0.39 (0.14)
P-PET	3	JJA	10	0.7 (0.03)	0.51 (0.04)
P-PET	3	SON	11	0.69 (0.02)	0.49 (0.04)
P	1	JJA	32	0.89 (<.0001)	0.7 (<.0001)
P	3	JJA	10	0.7 (0.03)	0.51 (0.04)
P	3	SON	11	0.62 (0.04)	0.45 (0.05)
PET	3	SON	11	-0.78 (0.005)	-0.49 (0.04)





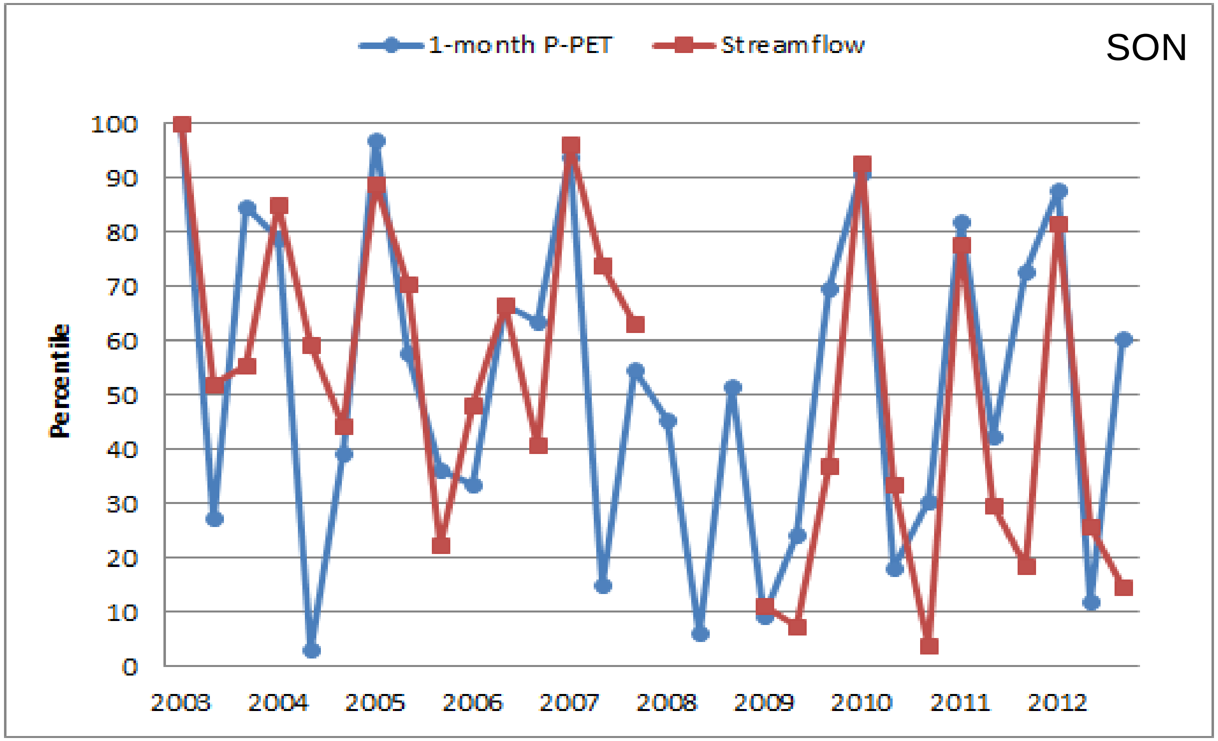
Results: Correlation with Streamflow in Dongjin-gang Watershed Basin

Variable	Time Scale (months)	Season	Sample Size	Pearson' r (p-value)	Kendall's tau (p-value)
P-PET	1	JJA	16	0.87 (<.0001)	0.65 (0.0004)
P	1	JJA	16	0.85 (<.0001)	0.68 (0.0002)

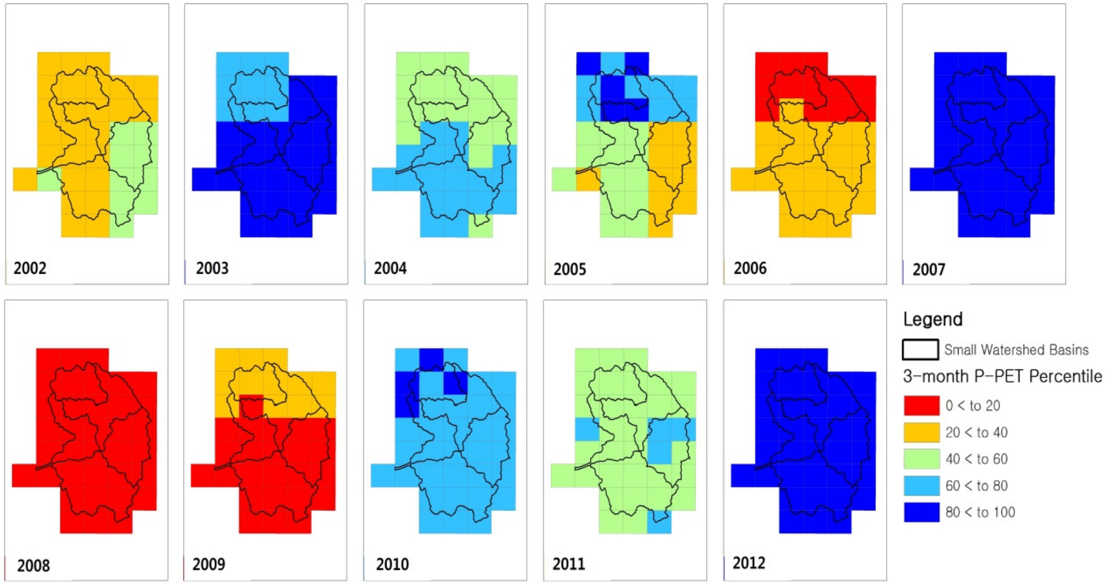


Results: Correlation with Streamflow in Upper Namhan-gang Watershed Basin

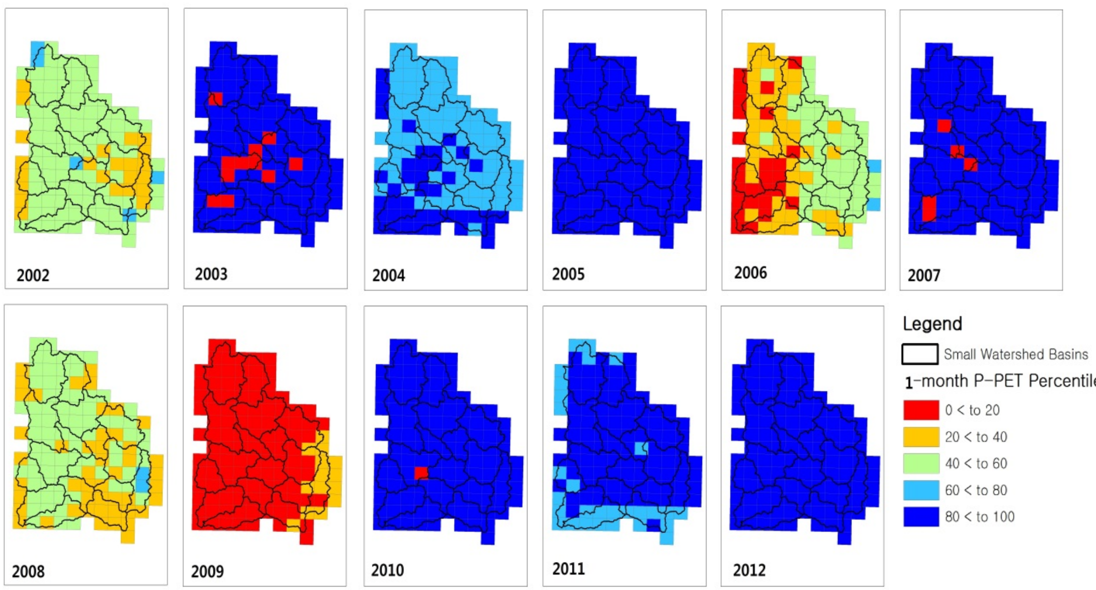
Variable	Time Scale (months)	Season	Sample Size	Pearson' r (p-value)	Kendall's tau (p-value)
P-PET	1	JJA	26	0.89 (<.0001)	0.71 (<.0001)
P-PET	1	SON	27	0.63 (<.0001)	0.47 (0.0006)
P	1	JJA	26	0.91 (<.0001)	0.75 (<.0001)
P	1	SON	27	0.64 (0.0003)	0.49 (0.0004)
PET	1	SON	27	0.51 (0.006)	0.38 (0.005)



Results: Gridded P-PET Percentile Maps



Gridded 3-month P-PET percentile maps in November (SON) in Mankyung-gang watershed basin.



Gridded 1-month P-PET percentile maps in September in Upper Namhan-gang watershed basin.

Conclusions

- Remote sensing-based P-PET can be used to assess hydrological drought in regions with limited observation data

- Input data for drought early warning systems can be produced, assisting decision-making processes to minimize adverse impacts of hydrological drought

- Drought information with high spatial resolution enables region-differentiated measures coping with drought in developing counties

Limitations and Further Study

- Spatial resolution of precipitation estimates
  - GPM (Global Precipitation Measurement) data available from 2014

- Effect of soil moisture and vegetation phenology on evapotranspiration

- More case studies in various climates needed

Thank you!

jyrhee@apcc21.org

www.apcc21.net
APEC Climate Center 12, Centum 7-ro
Haeundae-gu Busan 612-020 Korea
Tel : 82-51-745-3900 Fax : 82-51-745-3949

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